Lunar Inter-Calibration and Measuring Lunar Spectral Reflectance with CLARREO Pathfinder

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The lunar calibration system — operation

Because the Moon's appearance is continuously changing, to use it as a calibration target requires the capability to predict the brightness for any Moon observations made by an instrument.

This is accomplished using an analytic model, which can be computed for the specific geometric conditions (illumination and viewing) of the instrument's observations of the Moon.

The USGS lunar calibration system operates with the spatially integrated lunar irradiance. The model kernel provides the lunar disk-equivalent reflectance as a function of the geometric variables of phase angle and the lunar librations :

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$

$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

g = phase angle
ϕ = observer selenographic longitude
θ = observer selenographic latitude
Φ = selenographic longitude of the Sun

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The lunar calibration system — operation

Computing the model equation gives the lunar disk reflectance (A_k) at the 32 ROLO wavelengths. A representative lunar reflectance spectrum is then fitted to these A_k values.

The fitted reflectance spectrum is convolved with the instrument band spectral response functions and the solar spectrum to give the lunar irradiance (E_{M}) at the sensor band wavelengths :

$$E_{\mathrm{M}} = \frac{\Omega_{\mathrm{M}}}{\pi} \frac{\int A_{\mathrm{fit}}(\lambda)\, E_{\mathrm{Sun}}(\lambda)\, S(\lambda)\, d\lambda}{\int S(\lambda)\, d\lambda}$$

A_{fit} = lunar reflectance spectrum
E_{Sun} = Solar spectral irradiance
S = spectral response function
$\Omega_{\mathrm{M}} = 6.418\times10^{-5}$ sterad

Apply distance corrections: $$E'_{\mathrm{M}} = E_{\mathrm{M}} \left(\frac{1\,\mathrm{AU}}{d_{\mathrm{Sun-Moon}}}\right)^2 \left(\frac{384\,400\,\mathrm{km}}{d_{\mathrm{Moon-Obs}}}\right)^2$$

The final output E'_{M} is the lunar irradiance present at the instrument location at the time of the observation, in each sensor spectral band.

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Application to inter-calibration

Typical inter-calibration involves two instruments viewing the same ground (or cloud) target nearly simultaneously

- corrections for Sun and view angles : cosines, surface BRDF
- corrections for different sensor spectral response : SBAFs

For lunar calibration, the target (the reference standard) is represented by the computed output of the lunar model

- differences in the Moon's appearance accounted in the model kernel
- spectral response differences are accounted in the post-processing
  - no external SBAF correction is needed

Normalizing the sensors' measurements of lunar irradiance by the model results provides offsets against the lunar reference.

Comparison of these offsets yields the lunar inter-calibration

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Uncertainties of lunar inter-calibration

The accuracy of inter-calibration using the Moon as a transfer standard is constrained by the *relative* accuracy of the lunar reference (model)

- radiometric and geometric specification of the lunar irradiance (phase, librations)
- spectral specification of the lunar irradiance

For Moon observations with similar phase angles and similar sensor bands, the absolute scale of the lunar model has a second-order effect.

Currently the ROLO model is the most reliable lunar calibration reference available, but there are known limitations, *e.g.*

- absolute scale uncertainty is ~5-10%
  - value estimated based on comparisons of Moon measurements by many different instruments
  - this level of accuracy is insufficient for a primary on-orbit cal reference
- residual geometry dependencies, e.g. libration effects seen in the SNPP-VIIRS lunar calibration time series

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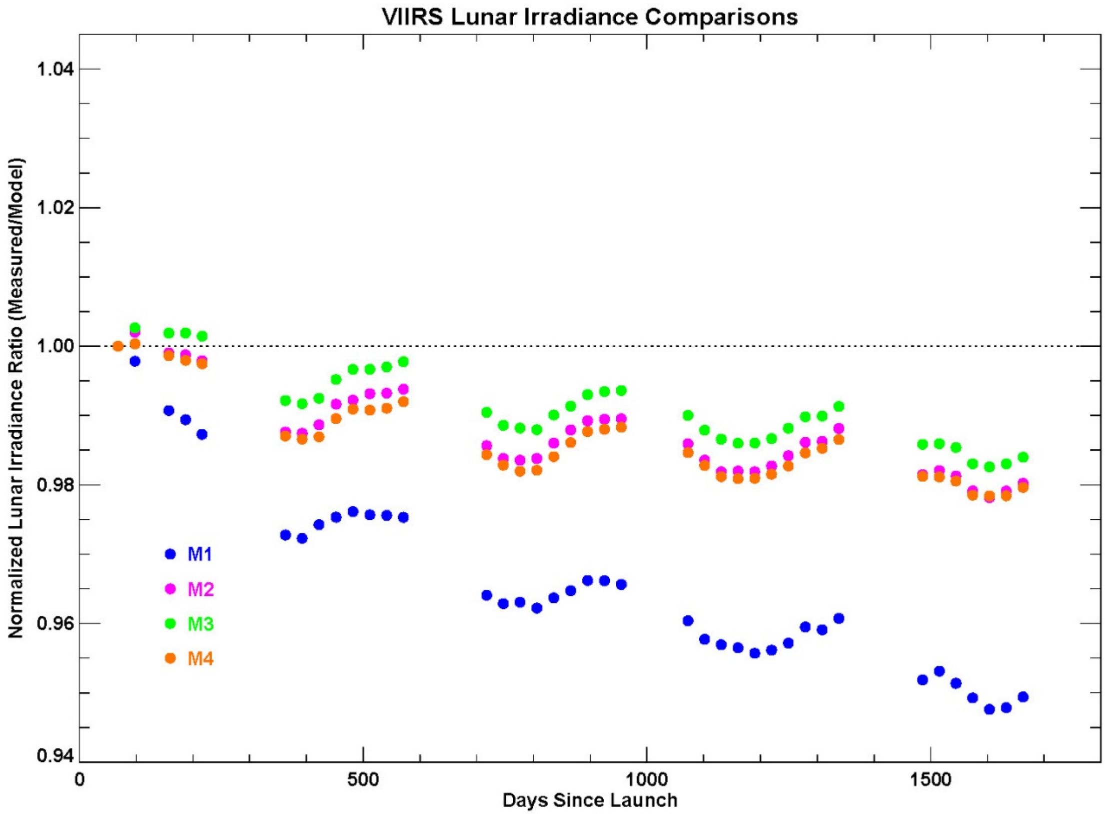
SNPP-VIIRS lunar calibration comparisons

Time series of lunar irradiance ratio : measurement / reference



- normalized to 2012-01-04 (68 days after launch)
- a smooth degradation trend is superposed with fairly regular oscillations
- oscillations are highly correlated among bands, and found to be correlated with the lunar librations

The high quality of VIIRS (and other) lunar measurements shows need for an improved lunar calibration reference.

Advancement of the lunar radiometric reference

The current absolute accuracy limitation is solely with the lunar model.

- tied to uncertainties in the ROLO dataset and model formulation (*i.e.* the specification of the lunar irradiance for different view geometries and wavelengths)
- the largest source of error in ROLO data is the atmospheric correction
  - derived nightly from star observations, but airmass range is limited to ≤2
  - applies also to Vega, which is the calibration reference for ROLO

The Moon potentially can provide an absolute calibration reference with uncertainty ≤1% (k=2).

To reach the full potential of lunar calibration requires collecting new measurements of the Moon, to use as a basis dataset for a revised model.

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CLARREO Pathfinder observations of the Moon

The HySICS concept for CLARREO Pathfinder does not utilize the Moon for on-orbit absolute calibration or instrument performance monitoring. (may need to be revisited due to Sun-viewing constraints)

However, lunar observations by CPF can provide :

- comparison of CPF spectral reflectance measurements against a known standard, potentially with sub-percent accuracy
- a reference for inter-calibration
- presuming the RS instrument achieves goals for on-orbit accuracy, characterization measurements of the Moon which potentially can constrain a future lunar model that becomes the calibration reference.

To achieve this last objective requires a program of Moon acquisitions.

Simulations of lunar observation opportunities from the ISS orbit show the temporal behavior of Moon view geometries. Practical viewing constraints will limit the geometric coverage available.

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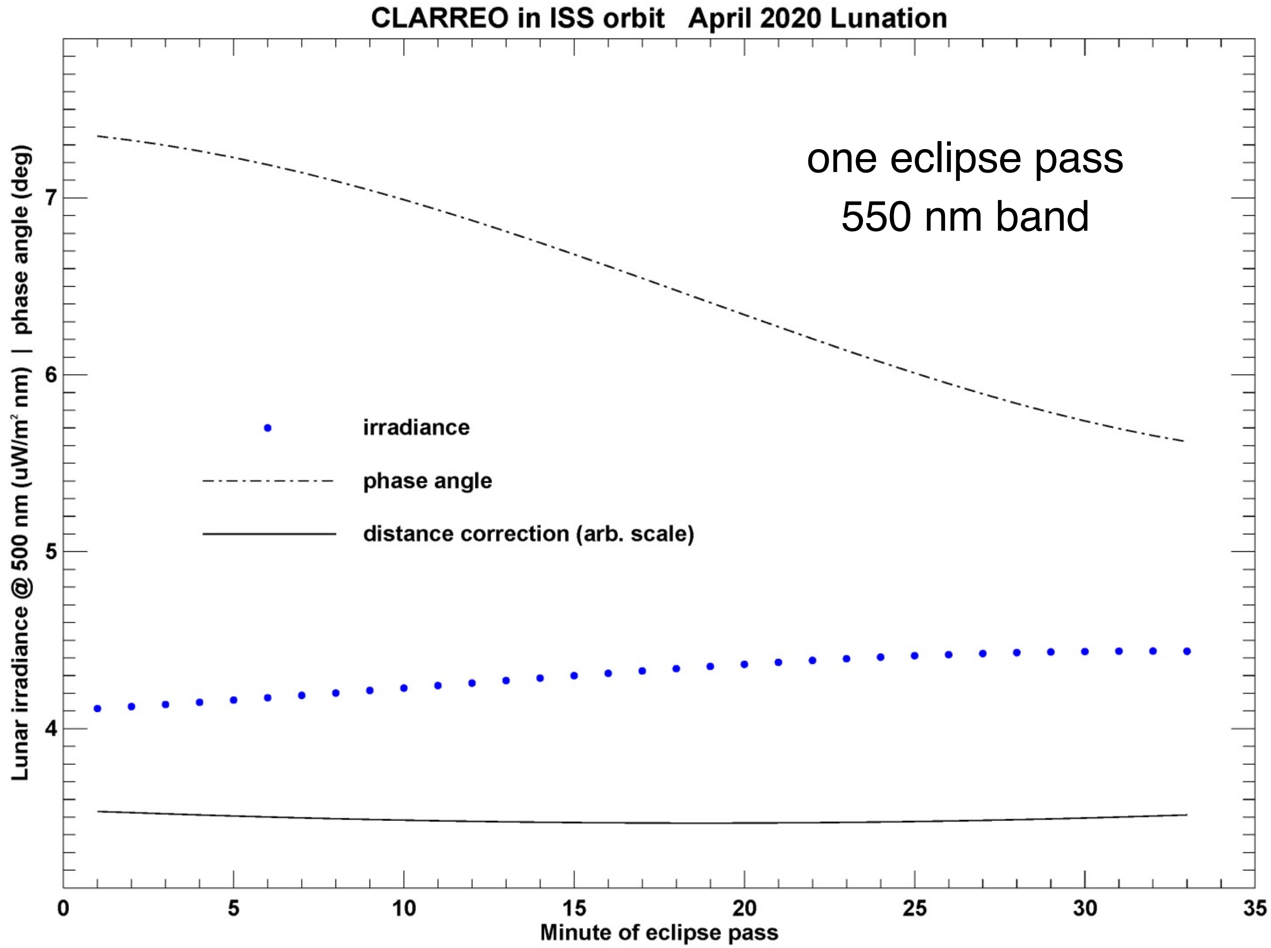
CLARREO Pathfinder observations of the Moon

Initial simulations assumed Moon observations are acquired only during eclipse parts of the ISS orbit. The spacecraft orbital motion affects the observation geometry.

The geocentric lunar phase angle increases monotonically with time. The observed behavior is due to the spacecraft position relative to the Moon.

Specific selection of observation times can give minimal change in the lunar irradiance with time.



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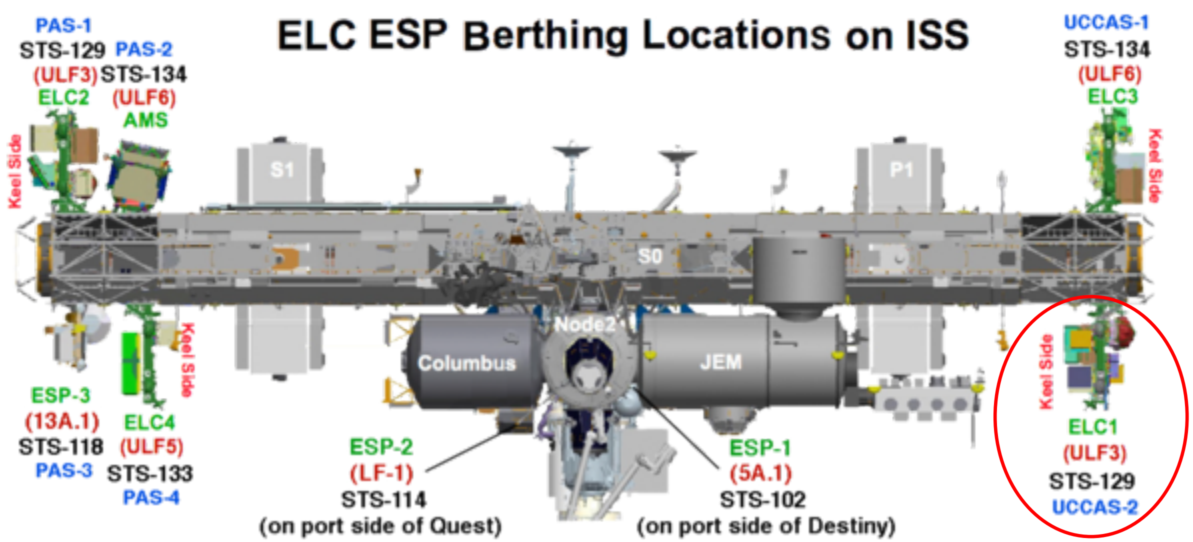
CLARREO Pathfinder observations of the Moon

CPF location at ELC-1 Site 3 is optimized for the CLARREO primary mission: benchmark Earth measurements and reference inter-calibration. The Moon observation simulations show :

- ISS orbit inclination of 51° has very little impact
- line of sight obstructions by the ISS superstructure and solar panels could impose significant limitations on Moon viewing opportunities.



CLARREO Pathfinder observations of the Moon

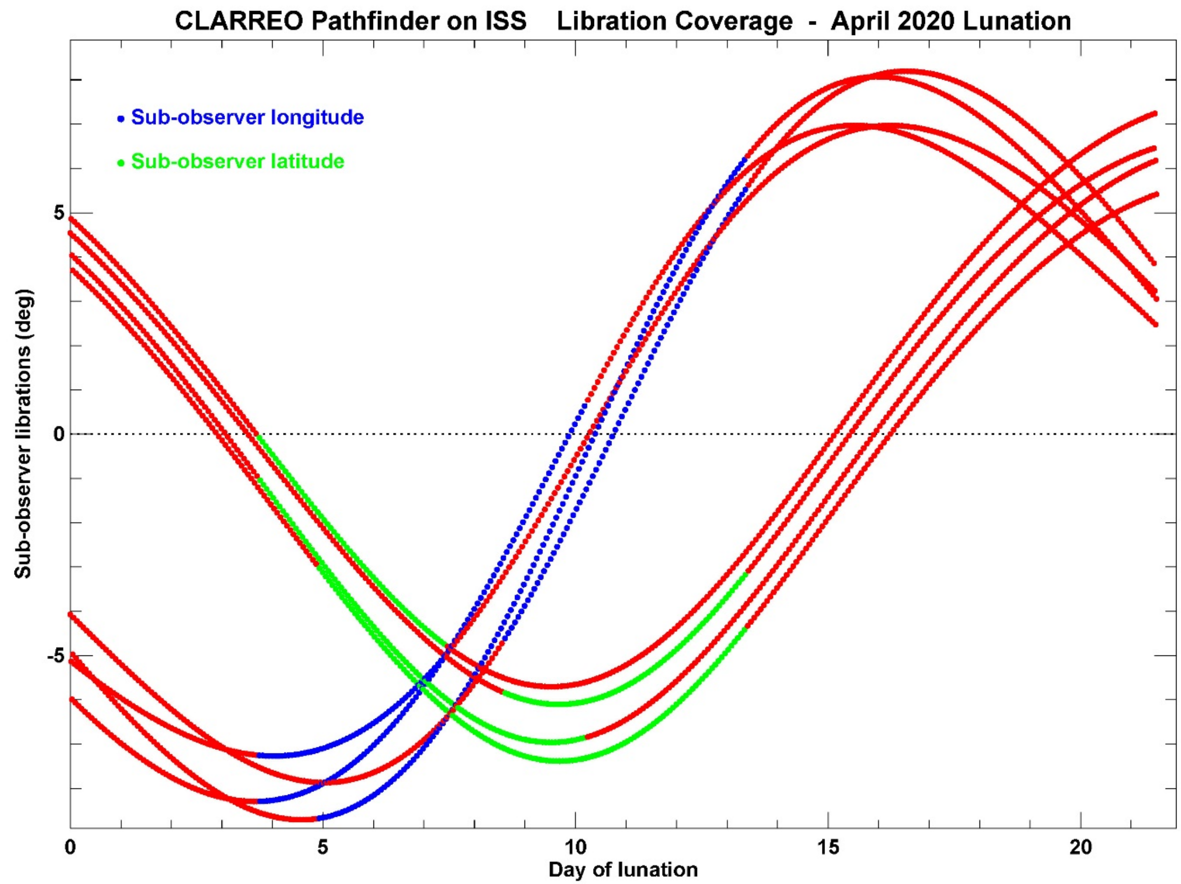
ELC-1 Site 3 is a port-side nadir location. Expanded simulations assumed minimal view obstruction constraints :

- the ISS truss limit views to 165° elevation angle
- the ELC pallet excludes views in the starboard direction

Plots of lunar libration coverage through one lunar cycle, with no eclipse constraint.

Plotted points are ascending and descending nodes, and N-S latitude extremes.

Less than 30% of opportunities have unobstructed views.



CLARREO Pathfinder observations of the Moon

Summary notes :

- additional simulations with more realistic ISS obscuration models will be necessary for mission operations
- careful selection of observation times can provide observing periods where the lunar brightness changes relatively slowly
- a 1-year operational lifetime will give very limited coverage of lunar observation geometries

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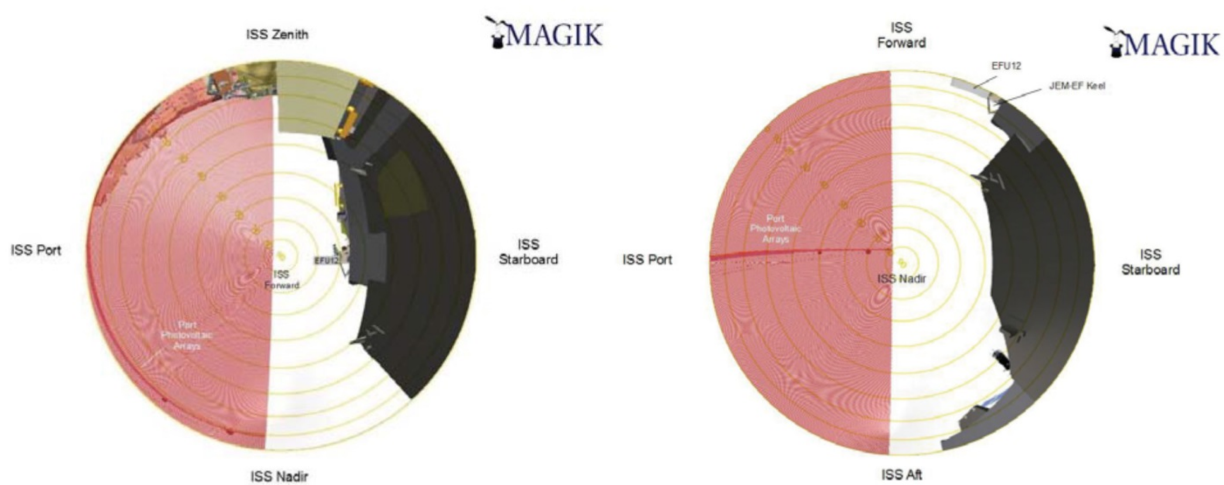

Figure 3.1.6-1. ELC-1 outboard ExPA payload accommodation forward (ram) and nadir.